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Performance of High-Frequency High-Flux Magnetic Cores at Cryogenic Temperatures

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PERFORMANCE OF HIGH-FREQUENCY HIGH-FLUX MAGNETIC CORES AT CRYOGENIC TEMPERATURES

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ABSTRACT

Three magnetic powder cores and one ferrite core, which are commonly used in inductor and transformer design for switch mode power supplies, were selected for investigation at cryogenic temperatures. The powder cores are Molypermalloy Core (MPC), High Flux Core (HFC), and Kool Mu Core (KMC). The performance of four inductors utilizing these cores has been evaluated as a function of temperature from 20 °C to –180 °C. All cores were wound with the same wire type and gauge to obtain equal values of inductance at room temperature. Each inductor was evaluated in terms of its inductance, quality (Q) factor, resistance, and dynamic hysteresis characteristics (B-H loop) as a function of temperature and frequency. Both sinusoidal and square wave excitations were used in these investigations. Measured data obtained on the inductance showed that both the MPC and the HFC cores maintain a constant inductance value, whereas with the KMC and ferrite core hold a steady value in inductance with frequency but decrease as temperature is decreased. All cores exhibited dependency, with varying degrees, in their quality factor and resistance on test frequency and temperature. Except for the ferrite, all cores exhibited good stability in the investigated properties with temperature as well as frequency. Details of the experimental procedures and test results are presented and discussed in the paper.

INTRODUCTION

Many deep space missions require power electronic components and systems that can operate reliably and efficiently in cryogenic temperature environments. Presently, spacecraft operating in the cold environment of deep space carry on-board a large number of radioisotope heating units (RHUs) to maintain an operating temperature for the electronics of approximately 20 °C [1]. This is not an ideal solution because the RHUs are always producing heat, even when the spacecraft is already too hot, thus requiring an active thermal control system for the spacecraft. In addition, they are very expensive and require elaborate containment structures. Therefore, electronics capable of operation at cryogenic temperatures will not only tolerate the hostile environment of deep space but also reduce system size and weight by eliminating radioisotope heating units and associated structures; thereby reducing system development and launch costs, improving reliability and lifetime, and increasing energy densities.

Most aerospace power management systems are DC-based. To supply loads at different voltage and power levels, switching regulators represent a viable class of power electronics circuits that convert unregulated DC input voltages into regulated DC outputs. The design of these converters to operate at cryogenic temperatures is expected to result in more efficient systems than room temperature systems. This improvement requires from better electronic switches and filter components that can operate at low temperatures [2].

A typical switching power converter consists of components such as switches (transistors and diodes), transformers, inductors and capacitors for filtering. These components are designed to operate at frequency that ranges from a few kHz to several MHz and at power levels that range from a few mWs to MWs. Inductors represent a key element in the design and operation of such regulators as they play an important role in the filter design to achieve the required level of power quality at both input and output terminals.

The core losses of amorphous and ferrite cores as a function of temperature were investigated in the temperature range of –150 °C to 150 °C [3–4]. The performance of MPC and high temperature superconducting (HTS) inductor in a boost converter was evaluated at cryogenic temperatures [5].

Magnetic powder cores are known to be an ideal choice for use in the design of inductors and transformers in switch-mode power supplies due to their low loss and high Q-factor. These powder cores, such as MPC, High Flux, and Kool Mu, offer soft saturation, high magnetic flux density (B_{max}) and excellent temperature stability [3–5]. Molypermalloy (MPC) powder cores can be manufactured with different permeability and varying core sizes. Inductors designed with this family of cores can operate in a temperature range between –65 °C and 125 °C with variation in their inductance value limited to less than 10% [6].

High Flux powder cores have higher energy storage capacity than MPC and Kool Mu cores. They are very close to MPC in terms of permeability and core size, and are commonly used in inductors, in-line noise filters, pulse transformers, and flyback transformers [7].

Kool Mu powder cores are distributed air gap cores formulated for low loss, high frequency applications or for extremely low magnetostriction power applications, such as in energy storage filter inductor in switch-mode power supplies. These cores also come in different permeability and sizes and are economically priced between MPC cores and ferrite cores [8].

Ferrite cores exhibit low loss characteristics and are designed to operate in the temperature range of –30 °C to 70 °C. They possess high permeability from 750 to 2000 and are ideal for high-frequency (20 kHz to 3 MHz) power supplies applications. Ferrite cores can be un-gapped or gapped for saturating or non-saturating modes for both inductor and transformer designs [9].

In this work, a ferrite core and three powder cores consisting of Molypermalloy (MPC), High Flux Core (HFC), and Kool Mu Core (KMC) were selected for characterization for potential use in extreme temperature environments. Some of the properties of these cores are listed in Table I [6–9]. Four inductors were designed using these four toroidal-shaped cores for evaluation under cryogenic conditions. All cores were wound with the same wire type and gauge to give equal values of inductance at room temperature. Measurements of each core inductance, Q-factor, resistance, and dynamic hysteresis-loop as a function of temperature were obtained in the frequency range from 1 kHz to 200 kHz. The test temperature ranged from 20 °C to –180 °C. The desired test temperature was obtained using a Sun Systems environmental chamber utilizing liquid nitrogen as the coolant. A temperature rate of change of 10 °C/min was used throughout this work. At every test temperature, the device under test was allowed to soak at that temperature for a period of 30 minutes before any measurements were made. After the last measurement was taken at –180 °C, the cores were allowed to stabilize to room temperature and then the measurements were repeated to determine if the thermal cycling had produced any effect on their operational characteristics.

RESULTS AND DISCUSSIONS

The inductance of the four cores as a function of frequency and temperature is shown in Figure 1. It can be clearly seen that all cores, at any given temperature, exhibit steady inductance value with increase in frequency up to 100 kHz. At the highest test frequency of 200 kHz, however, the ferrite core declines slightly while the other three cores undergo slight increase. In terms of temperature, the MPC and the High Flux cores do not exhibit much variation in their inductance between 25 °C and –190 °C. The ferrite and the Kool Mu cores, on the other hand, suffer a reduction in their inductance as temperature is decreased. These temperature-induced changes are evident at every test frequency.

TABLE I. PROPERTIES OF MAGNETIC CORES [3–6].

Core	Outer Dia. (in.)	Inner Dia. (in.)	Height (in.)	Temp (°C)	μ_r
MPC	1.06	0.58	0.44	–65 to 125	125
KMC	1.06	0.58	0.44	–65 to 125	125
HFC	1.06	0.58	0.44	–65 to 125	125
Ferrite	0.88	0.58	0.22	–30 to 70	900

With the exception of the ferrite core, all cores display typical characteristics in their quality factor with frequency as shown in Figure 2. The MPC, High Flux, and the Kool Mu cores attain a peak value in their Q-factor between 80 and 180 in the vicinity of a frequency of 10 kHz. This peak, however, shifts toward lower frequency as test temperature is decreased. The ferrite core, on the other hand, exhibits inconsistent behavior in its Q-factor with frequency as shown in Figure 2. While it initially increases with frequency up to 10 kHz, the quality factor begins to decline, remains steady, or increases afterwards. These trends in the variation of the quality factor at frequencies above 10 kHz seem to be dependent on the test temperature. At 25 and –50 °C, for example, the Q-factor increases with increase in frequency, while the opposite holds true at –100 and –150 °C. At temperature of –190 °C, the ferrite core maintains a relatively steady value in its quality factor throughout the entire frequency range.

Figure 3 depicts the resistance of the cores as a function of frequency at various temperatures. All cores exhibit similar trend in this property with both test parameters. It can be clearly seen that while the resistance of any of these cores remain unaffected with frequency up to 100 kHz, it dramatically increases as the frequency is increased further. This is due to the fact that the ac core and wiring losses portion of the inductor resistance become more dominant at high frequencies. The effect of temperature is more noticeable in the flat region where the resistance, as expected, drops down in value with a decrease in temperature.

The inductor response to a 100 kHz square wave input excitation is shown in Figure 4 for all four cores at 25 °C and at –180 °C. While not much variation is observed in the response behavior of the MPC, HFC, and KMC cores at the two different test temperatures, the ferrite core exhibits a significant increase in the intensity level associated with a mild saturation-like distortion in its inductor current at the extreme temperature of –180 °C. The loss of the inductance of this core, as was shown in Figure 1, is largely responsible for the increase in this inductor current.

The dynamic hysteresis characteristics of the tested cores are displayed in Figure 5 at room temperature as well as –180 °C. These characteristics, which are represented by the B-H loops, are indicative of the core loss of the magnetic materials. These loops are obtained by integrating the coil voltage and plotting it against its excitation current. It can be seen that the ferrite core, unlike the other three cores, exhibits a great dependency in its loss characteristics on temperature. A drastic increase in core loss, i.e., widening of the B-H loop, occurs at the extreme temperature of –180 °C for this type of magnetic material.

CONCLUSION

Four different types of magnetic cores were investigated for potential use in cryogenic applications. These cores consisted of a ferrite and three powder-based cores. The powder cores were Molypermalloy (MPC), High Flux (HFC), and Kool Mu (KMC). The performance of four inductors utilizing these cores has been evaluated as a function of temperature from 20 °C to –180 °C. Each inductor was evaluated in terms of its inductance, quality (Q) factor, resistance, and dynamic hysteresis characteristics (B-H loop) as a function of temperature and frequency. The results obtained on the inductance showed that both the MPC and the HFC cores maintain a constant inductance value, whereas the KMC and Ferrite hold steady values in inductance with frequency but decrease as temperature is decreased. All cores exhibit dependency, with varying degrees, in their quality factor and resistance on test frequency and temperature. Except for the ferrite, all cores exhibited good stability in the investigated properties with temperature as well as frequency. Further and more comprehensive testing is, however, required to access performance of these cores under long-term exposure to low temperature.

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9. "Ferrite Cores," Magnetics, Inc., Brochure FC–601–11H.

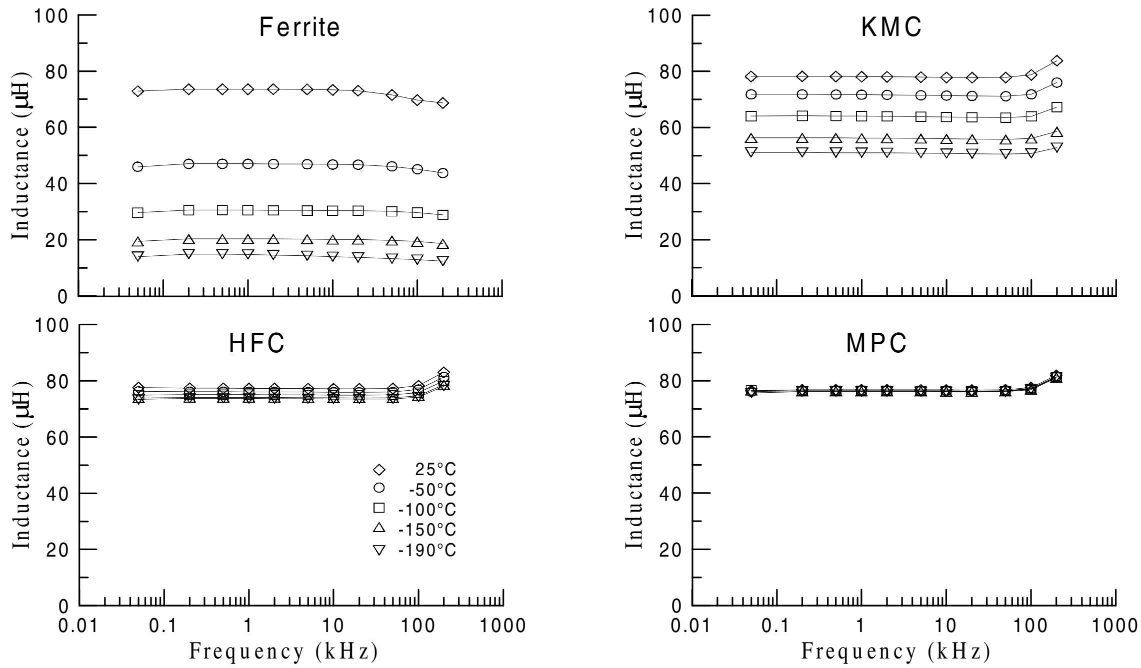

Figure 1. Inductance variation with temperature and frequency.

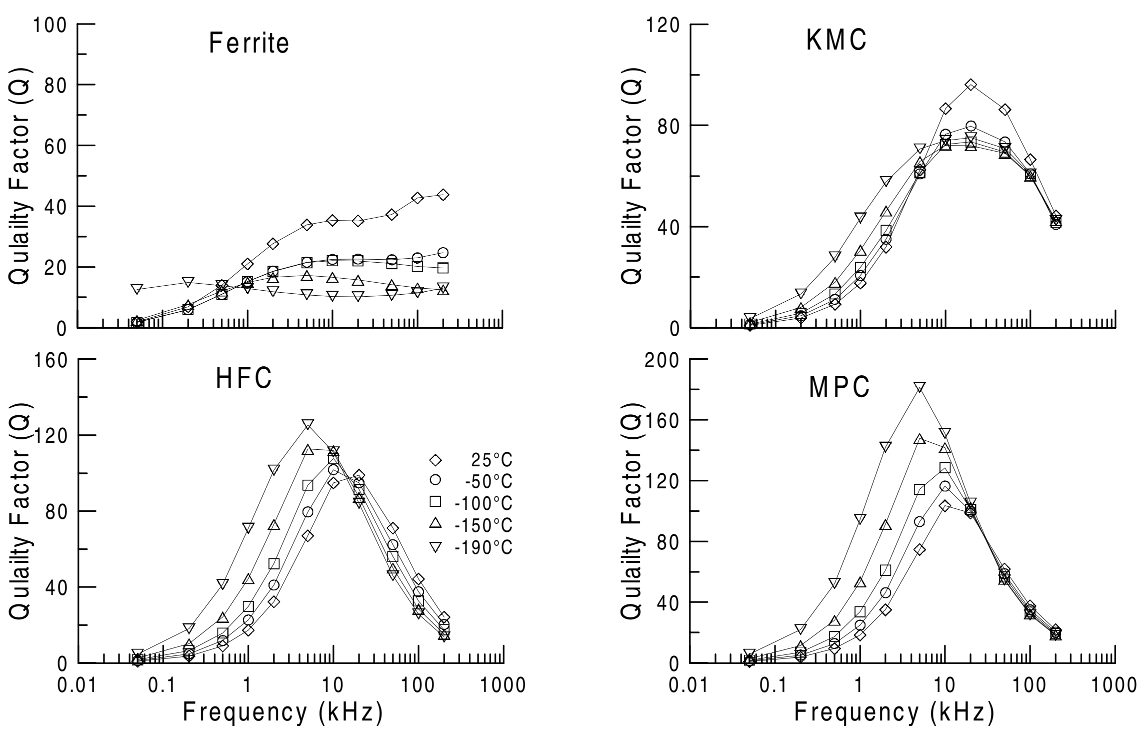

Figure 2. Quality Factor variation with temperature and frequency.

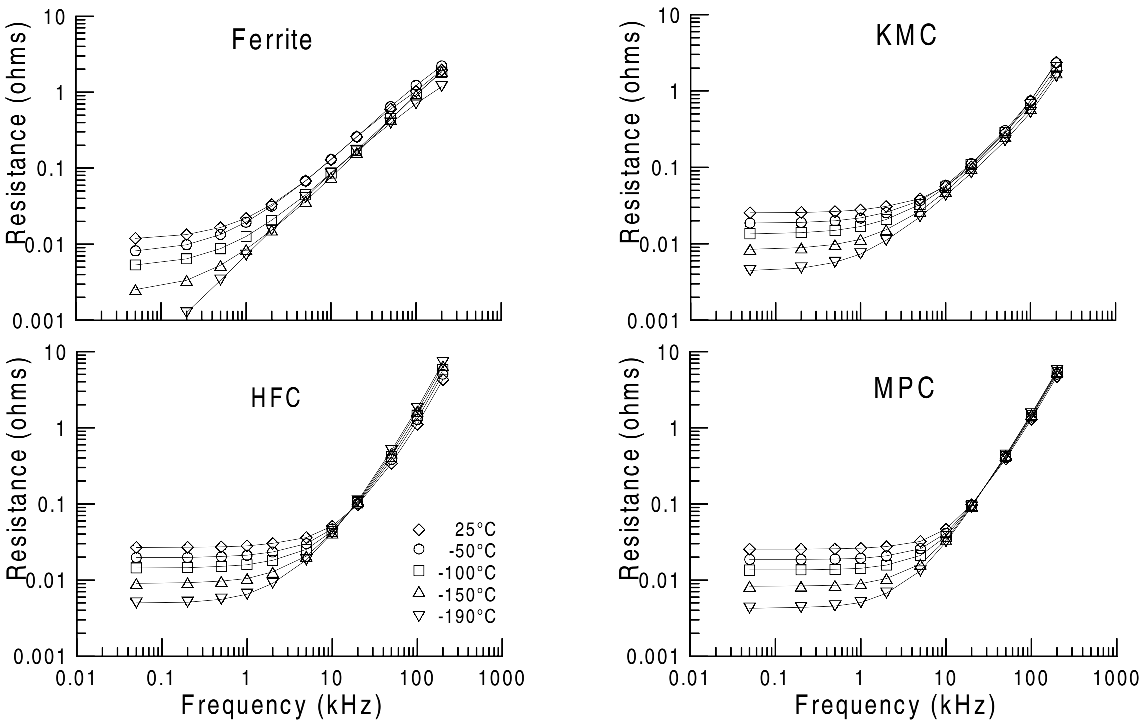

Figure 3. Resistance variation with temperature and frequency.

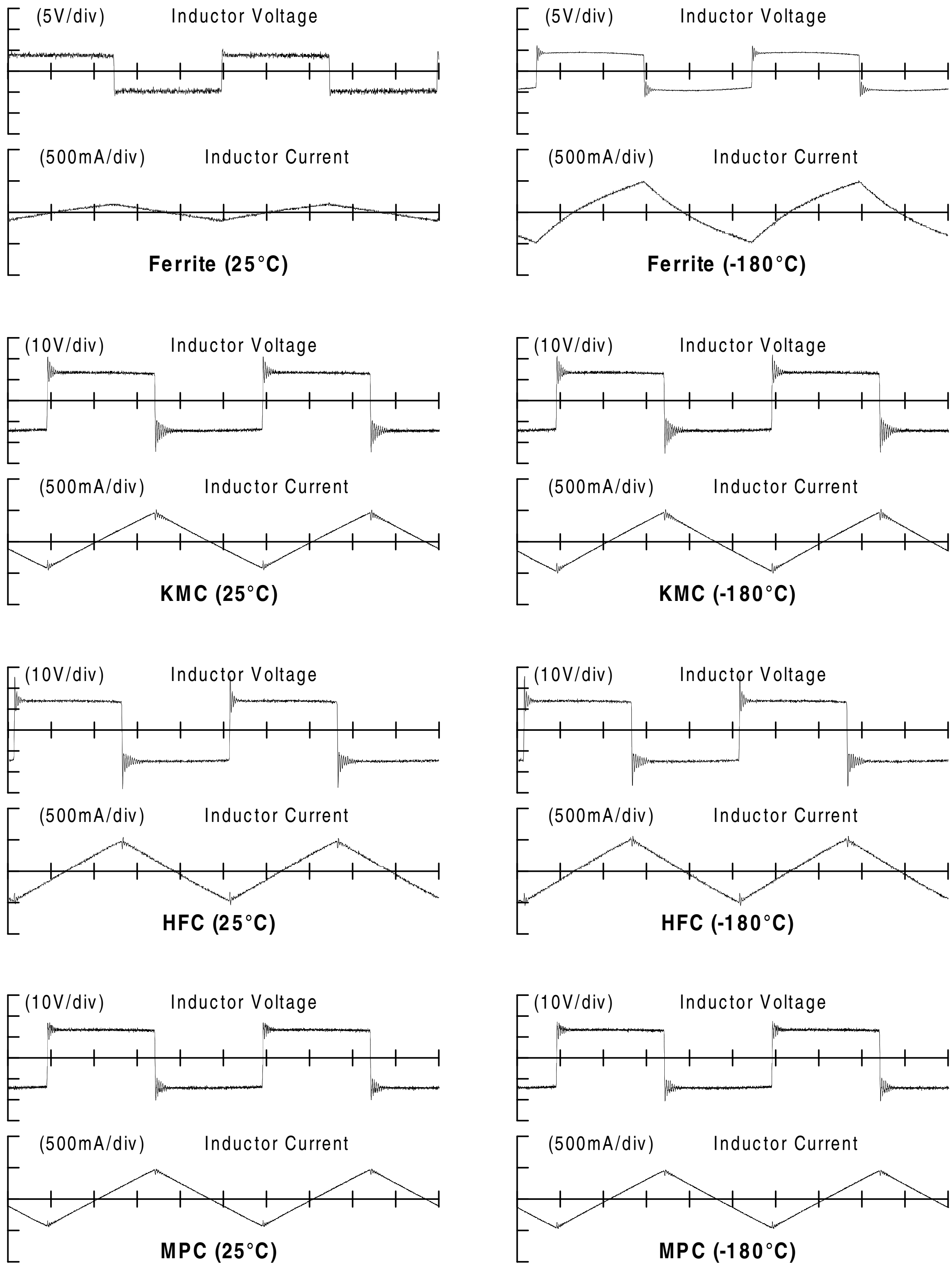

Figure 4. Response of inductors to a 100 kHz square wave excitation.

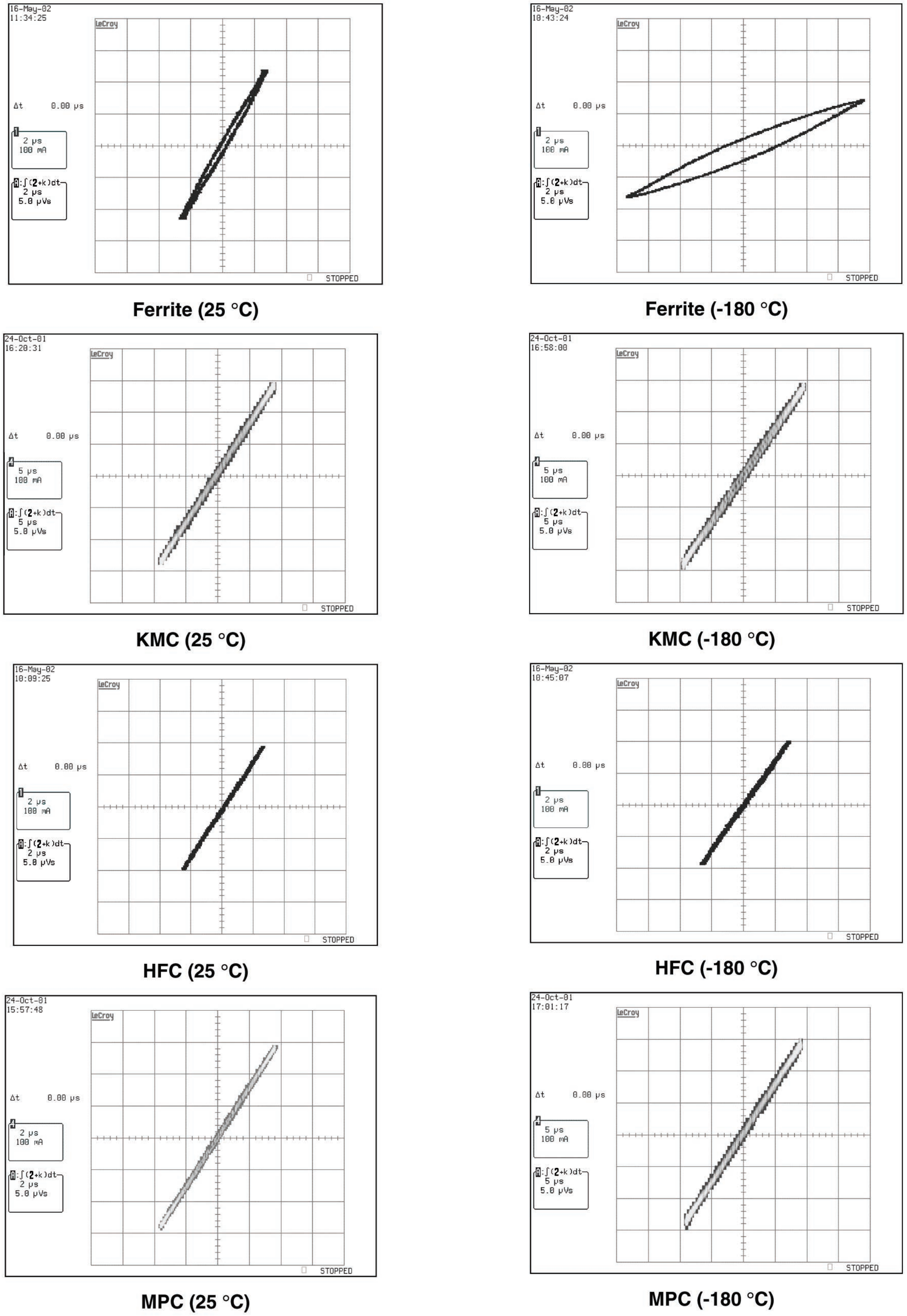

Figure 5. Effect of temperature on dynamic hysteresis characteristics.

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13. ABSTRACT ***(Maximum 200 words)***

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